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ADAPTIVE BEAM ANTENNA COMMUNICATION NETWORKS

Stanford Telecommunications Incorporated

D. Thomas Magill

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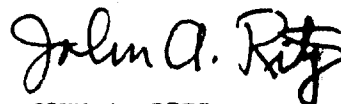
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SUMMARY

This study was devoted to assessing the feasibility of using an adaptive beam antenna system with a communication network to improve system performance. This assessment entailed developing beam acquisition algorithms, determining their practicality, and estimating their performance. Task objectives were to: 1) develop an integrated adaptive beam communication system, 2) determine the applicability of an adaptive beam antenna system, 3) determine the required adaptive beam antenna characteristics, and 4) define a demonstration system to be developed in Phase II of this effort.

Our general methodology was based on literature review, analysis, and synthesis. Through serendipity our review of the spread spectrum literature lead us to develop an innovative beam acquisition algorithm based on beam scanning sequences derived from Latin squares. (We believe our study is the first to propose Latin square beam scanning sequences.) These scanning sequences offer performance advantages as well as very substantial equipment simplification since a common transmit and receive pattern can be employed. Furthermore, we have devised an effective technique for unsynchronized net entry that is compatible with Latin square scanning. In effect, the Latin square beam acquisition algorithm developed in this study make it practical to use an adaptive beam antenna system in a communication network.

Consequently, we conclude that an adaptive beam antenna system is practical to implement and offers substantial performance improvements for communication networks - independent of whether an existing modem or an integrated modem, designed specifically for the adaptive beam network is used. Based on this conclusion we present a development plan for a demonstration network.

SECTION 1

INTRODUCTION

This report presents the results of our study of the use of adaptive beam antenna systems to greatly improve the performance of communication networks. The study concentrated on the systems aspects of adaptive beam antennas system as opposed to the technology for implementation of such system. Thus, for example, our study concentrated on items such as beam scanning patterns, net entry algorithms, and network performance.

This study was performed under a Phase I effort of a small business innovations research (SBIR) contract. The favorable results obtained suggest that it is highly desirable to perform a Phase II effort which would develop and demonstrate an adaptive beam antenna system for a communication network.

We are particularly pleased to present a beam acquisition algorithm based on the innovative use of beam scanning patterns derived from Latin squares. This technique was not presented in our proposal and is the direct result of this study. This beam acquisition technique offers substantial equipment simplification and performance advantages as compared to the techniques presented in our proposal, e.g., progressive beamwidth reduction or selective scanning. We believe that the Latin square beam scanning technique makes adaptive beam antenna systems much more feasible for network applications than any other scanning algorithm.

We begin our report with basic antenna system considerations in Section 2. Section 3 presents an investigation devoted to the design of the beam acquisition and steering signal.

Beam acquisition and tracking algorithms for the link and network environments are presented in Sections 4 and 5, respectively.

Section 6 considers beam scheduling issues and techniques for the communication function. The applicability of adaptive beam antenna systems to selected existing communication modems is investigated in Section 7. Finally, Section 8 presents a demonstration system plan.

SECTION 2

BASIC ANTENNA SYSTEM CONSIDERATIONS

In this section we consider the major aspects of antenna systems and their impact on the adaptive beam antenna system which is the subject of this report. Our goal is to reduce the range of antenna system characteristics to those that are practical and suitable for use in an operational adaptive beam antenna system.

First, we compare multi-beam antennas (MBA) with phased arrays and recommend the former as the basis of our investigation. [Refs. 2-1, -2, and -3]. We then consider the possible beam configurations. Finally, we consider the required beam switching networks for the adaptive MBA system. Owing to their importance the beam scanning algorithms are presented in Sections 4 and 5 for link and network environments, respectively.

2.1 COMPARISON OF MULTI-BEAM ANTENNAS (MBA) VERSUS PHASED ARRAYS

The advantages of the MBA system are: 1) simple control since it is not necessary to adjust phase as is the case with a phased array, 2) a better pattern, in general, and 3) a simpler discrete search algorithm as compared to a continuous search.

The disadvantages are that: 1) it may be more difficult to construct MBAs in the lower frequency ranges, and 2) it may be more difficult to adequately track moving targets.

The advantages of the phased array are: 1) the ability to create an arbitrary pattern, and 2) the ability to operate better at lower frequencies for a given size antenna.

The disadvantages of the phased array are: 1) the complex and costly amplitude and phase weighting components required, 2) the relatively high sidelobe levels associated with phased arrays of moderate (or low) complexity, and 3) the potential necessity of including mutual coupling effects between the array elements [Ref. 2-4].

In general, the MBA approach appears preferable but the selection process must represent practical factors. For example, selection of a carrier frequency at VHF or

lower could well dictate the use of phased arrays. In any event development of the beam acquisition and tracking algorithms for an MBA system serves as a useful basis for the development of the algorithms for a phased array system. In the latter case the principal difference is that it is possible to synthesize beams in a continuum of angular directions thereby avoiding some of the beam cross-over issues with the MBA. In terms of assessing the direction of arrival the MBA faces a decision between multiple discrete choices whereas the phased array could be operated either in the discrete choice decision mode or, alternatively, in the estimation mode (a continuum of possibilities) if so desired.

Since the MBA system can serve as a basis for a phased array approach this study will be devoted to the discrete beam acquisition and tracking problem.

2.2 BEAM CONFIGURATIONS

Depending on the proposed application a variety of beam configurations is possible. For example, one might have a two-dimensional planar array permitting beam selection both in azimuth and elevation. Alternatively, one might use a one-dimensional array permitting scanning only in azimuth. Such a linear array could cover only a restricted sector or could cover a full circle.

For the purpose of this study we restrict our consideration to a circular array of elements permitting a search in azimuth over 2π radians of arc. We assume the probability density of the direction-of-arrival (DOA) for other nodes is uniform over 2π radians. If the distribution were non-uniform our scanning algorithms could be modified to take advantage of this a priori information and reduce the average acquisition time. Similarly a smaller sector of arc than 2π radians would shorten the search. In this study we develop our analyses and techniques for the most difficult case.

Extension to searching both in elevation and azimuth is straightforward and will not be considered further here. It should be noted that substantially longer acquisition times will result if it is necessary to scan in elevation as well as azimuth.

2.2.1 Azimuthal Omnidirectional Antenna Array

In order to achieve an omnidirectional pointing capability it is necessary to have a circular or near circular array of elements. These elements could be either directional

or omnidirectional elements. In the latter case the antenna system is a phased array. In the former case (assuming narrow beams) a multiple beam antenna (MBA) results. For our proposed application a phased array, while possible, presents two significant problems. First, it would be necessary to account for the mutual coupling effects between the elements. Second, since the elements are not configured in a linear array it is necessary to provide phase compensation to accommodate the resultant phase shifts at each element.

Often MBA arrays are designed so that several, if not most beams are excited simultaneously [Ref. 2-5]. Such an arrangement provides greater directivity than that of a single element. However, it requires more complex and costly components. Greater efficiency can be achieved with the use of switches rather than amplitude and phase control circuits. Furthermore, the associated tracking and acquisition algorithms are considerably simpler when there is a discrete number of beams. As a consequence our proposed adaptive beam antenna systems will nominally consist of M beams arrayed in a circular fashion. If need be, our results could be extended to phased array implementations as well.

Since it is not possible to design ideal beams with no sidelobes and since no gaps in coverage are desired, inevitably there will be some beam overlap. Clearly, one needs to design for the correct amount of overlap. A nominal design of a 3 dB crossover is reasonable. With such a design the maximum loss one encounters is 3 dB. A smaller crossover loss is desirable but such a design makes it more difficult to distinguish between two beams. In other words the beam skirt selectivity increases with the crossover loss (i.e., the gain loss at the midpoint between two adjacent beams).

Increasing the crossover loss reduces the probability of beam confusion but increases the likelihood that the desired signal might be missed owing to the reduced signal strength near the crossover.

Steep skirt selectivity is desirable as it enhances LPI and AJ performance. However, if the skirt selectivity is too high in the regions of crossover it will be difficult to maintain contact with a moving node as it crosses from one beam to the next. Thus, skirt selectivity (and beam overlap) should be selected as a compromise between LPI and AJ performance and tracking performance.

It is helpful to consider an example of the physical and electrical properties of such an array. Assume that one wishes to operate at a frequency in the range of 1.6 GHz. In this case, it is feasible to use circularly, polarized, helical antennas. It is possible to obtain a 3 dB bandwidth of 36° so that 10 elements would suffice to provide full azimuthal coverage. Such a helical antenna element, including an integral radome, would have a base plate of 7 inches in diameter and overall dimensions would be approximately 16 inches in length and $2\frac{1}{2}$ inches in diameter. The entire array could be placed within a 5 foot diameter circle. Thus, it is practical to mount on a small tower.

2.2.2 Design Factors in the Choice of the Number of Beams

Clearly the larger the number of beams (M) the larger the antenna gain which means that 1) the communication link budget is enhanced by a factor of M^2 , 2) the LPI is enhanced by a factor M ,* and 3) the spatial AJ processing gain is enhanced by a factor of M . Furthermore, the immunity to self interference from other undesired network nodes has been increased by a factor of M^2 .

The above results are based on the assumption that a fixed transmitter power is used. If the transmit power was reduced so that the transmit EIRP were maintained independent of M the communication link budget would be enhanced by M . The LPI enhancement remains at a factor of M as does the spatial AJ processing gain.

If the transmit power were reduced proportioned to M^2 so that the link budget were maintained constant, the results would be the same except for the link budget.

For tactical situations, it is reasonable to assume that the transmit power is constant. Thus, the link budget is proportioned to M^2 . In this case the absolute AJ performance (assuming a constant data rate) is proportioned to $M^3 - M^2$ from the link budget and M from spatial processing gain.

The above computations clearly indicate the desirability of a large M . On the negative side a large M means more costly and complex equipment. Furthermore, the beam acquisition time increases in proportion to M^2 for a constant beam dwell time. However, if

* We assume that the signal is detectable by an unfriendly observer independent of the EIRP. The factor assumed to effect detectability is simply the beamwidth.

the beam dwell time can be shortened proportional to the gain in the link budget there is no net increase. In any event the complexity of the algorithm increases since it is necessary to keep track of a larger number of beams at each node.

At lower frequency bands it is difficult to achieve narrow beamwidths in an antenna system size practical for tactical applications. At VHF about the best one might expect to achieve realistically is 4 or 8 beams. For the purposes of the study we consider the number of beams to range between 4 and 32. Larger values while desirable are not practical to implement.

2.3 BEAM SWITCHING NETWORKS

The beam switching network is of great importance to adaptive beam antenna systems since it directly affects system performance and complexity and cost. Initially, we consider configurations that only accommodate the antenna beam steering subsystem itself. Later, we consider the impact of adding the communication equipment.

Figure 1 is a block diagram of the simplest configuration. A single set of electronics consisting of duplexer, high power amplifier (HPA), up- and down- converters, and beam steering modem is shared between different beams through a single-pole, multiple-throw switch (SPMT) operated by a controller which may or may not interact with the beam steering modem depending on the scanning algorithm.

The advantage of this first configuration is its simplicity. The disadvantage is that the SPMT switch must handle the full HPA power. Readily available fast-acting switches are restricted to handling power levels below 10 or 20 watts.* Typical switches operate in 1 or 2 microseconds and handle 1 or 2 watts of average power. Significantly higher power levels can be handled with electromechanical switches but the switching times will be increased to 10 or 20 ms. An additional disadvantage is that both the receive and transmit functions are penalized by the loss of the duplexer and the RF switch. A reasonable estimate for the sum of these losses is about 2 to 3 dB. This is a significant loss for the transmit side. For the lower frequency bands the receive side loss may not

* Custom designed units are advertised in trade journals as being capable of handling 10 KW peak and 500 W average power at frequencies as high as S-band.

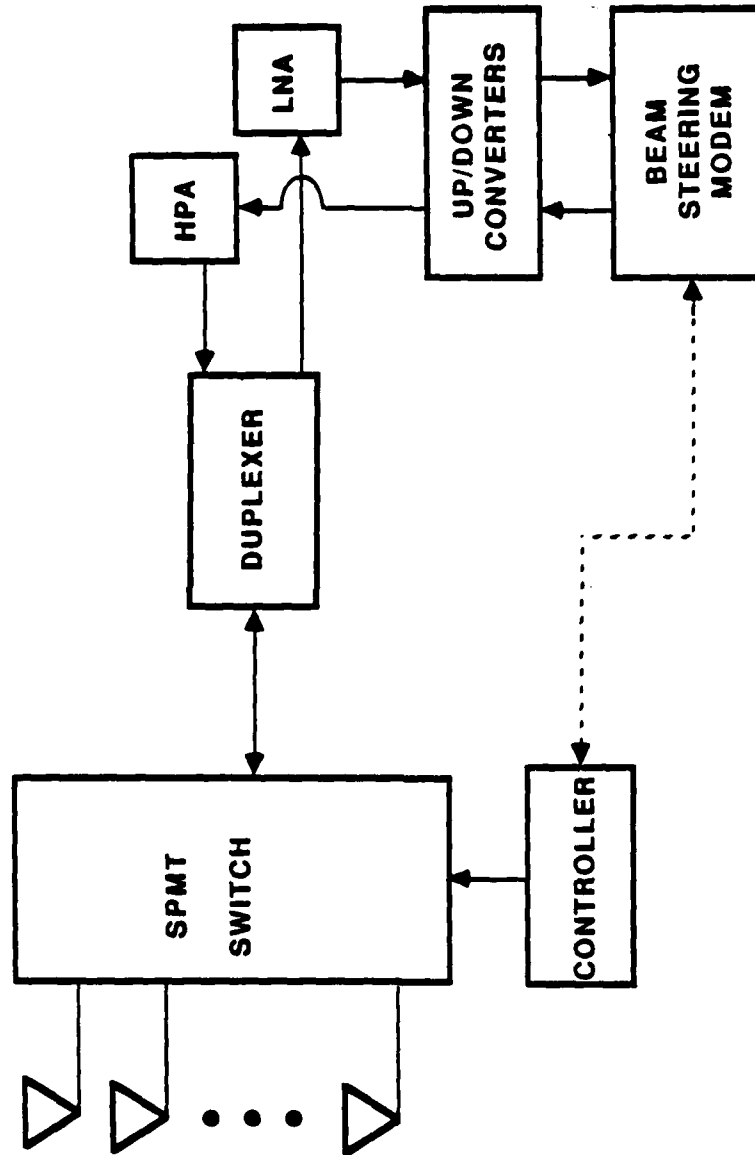


FIGURE 1 BLOCK DIAGRAM OF SIMPLEST ADAPTIVE BEAM CONFIGURATION

be significant since man-made noise may be larger than thermal noise. In any event, the losses are offset by the increased gain of each antenna beam.

Functionally, the major disadvantage of this simplest configuration is that it is not possible to separate the transmit and receive beam scanning patterns. Thus, for example, the selective scanning algorithm discussed in Section 4.2-1 is not possible with this configuration since it requires separate SPMT switches for transmit and receive.

The second or RF modular configuration shown in Figure 2 uses separate HPAs, LNAs, and duplexers for each beam. The advantages of this configuration are that the SPMT switch does not have to handle the HPA output power level and that the SPMT switch loss does not affect the output power level. This configuration results in a costly system owing to the M-fold replication of the front-end RF equipment and the duplication of the SPMT switch. However, if the power level and switching speed requirements so dictate it may be necessary to use this configuration which, in addition, permits separate transmit and receive scanning patterns.

The third configuration shown in Figure 3 is a hybrid between the first two configurations. As compared to the second configuration there is a savings in the number of LNAs. However, the received signal encounters the loss of the SPMT switch prior to the LNA (in contrast to the configuration of Figure 2).

Let us now consider the practical situation when a separate communication transceiver is required and is accommodated in a separate frequency band.* Figure 4 is a block diagram of one approach. With this approach the principal design issue is how the two SPMT switches are connected to the individual antenna elements. The standard approach would use a 3 dB hybrid and terminated (or absorptive) switches. As a result a loss in excess of 3 dB occurs for both the transmit and receive functions. The alternative approach would use reflective switches and simply connect the coaxial cables with a T. This approach is only practical if the cable lengths between the two switches and the Ts can be kept very short. When physically feasible this approach offers a much lower loss for both the transmit and receive functions. In general, this approach does not appear to be very desirable.

* In most cases there is little point in correctly aligning beams unless communication is to take place. If existing communication equipment is to be employed in an adaptive beam steering system it is best placed in a separate frequency band.

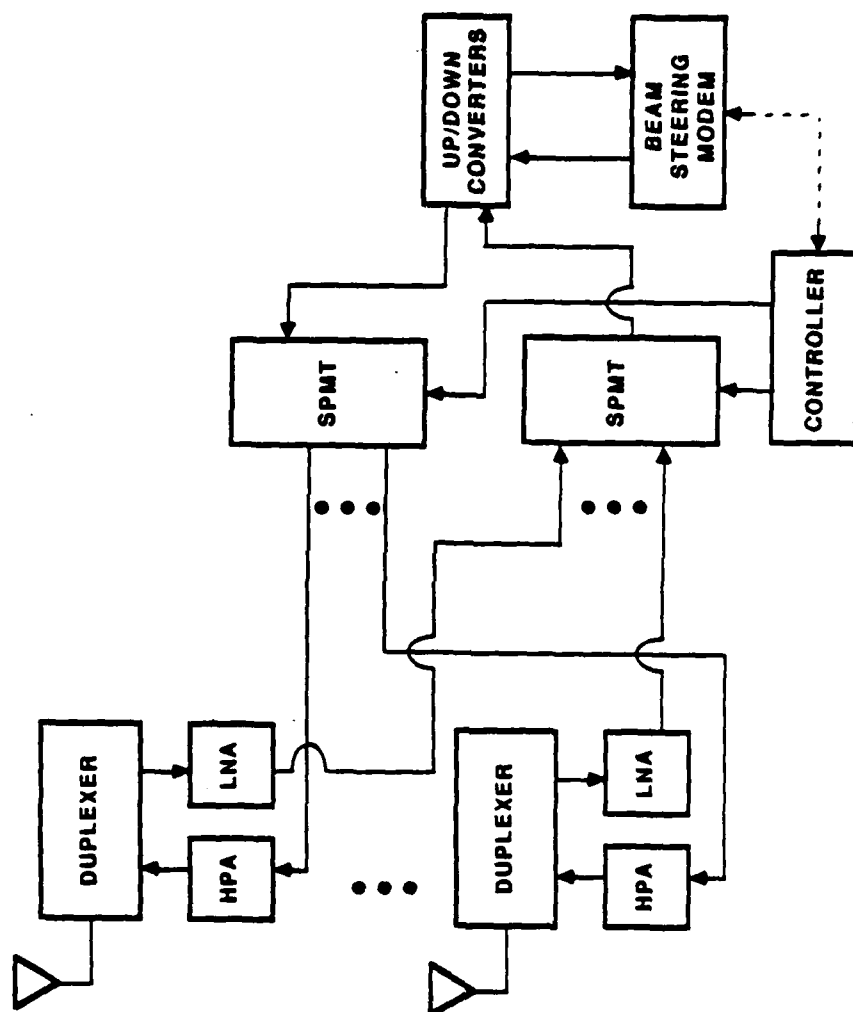


FIGURE 2 BLOCK DIAGRAM OF RF MODULAR CONFIGURATION

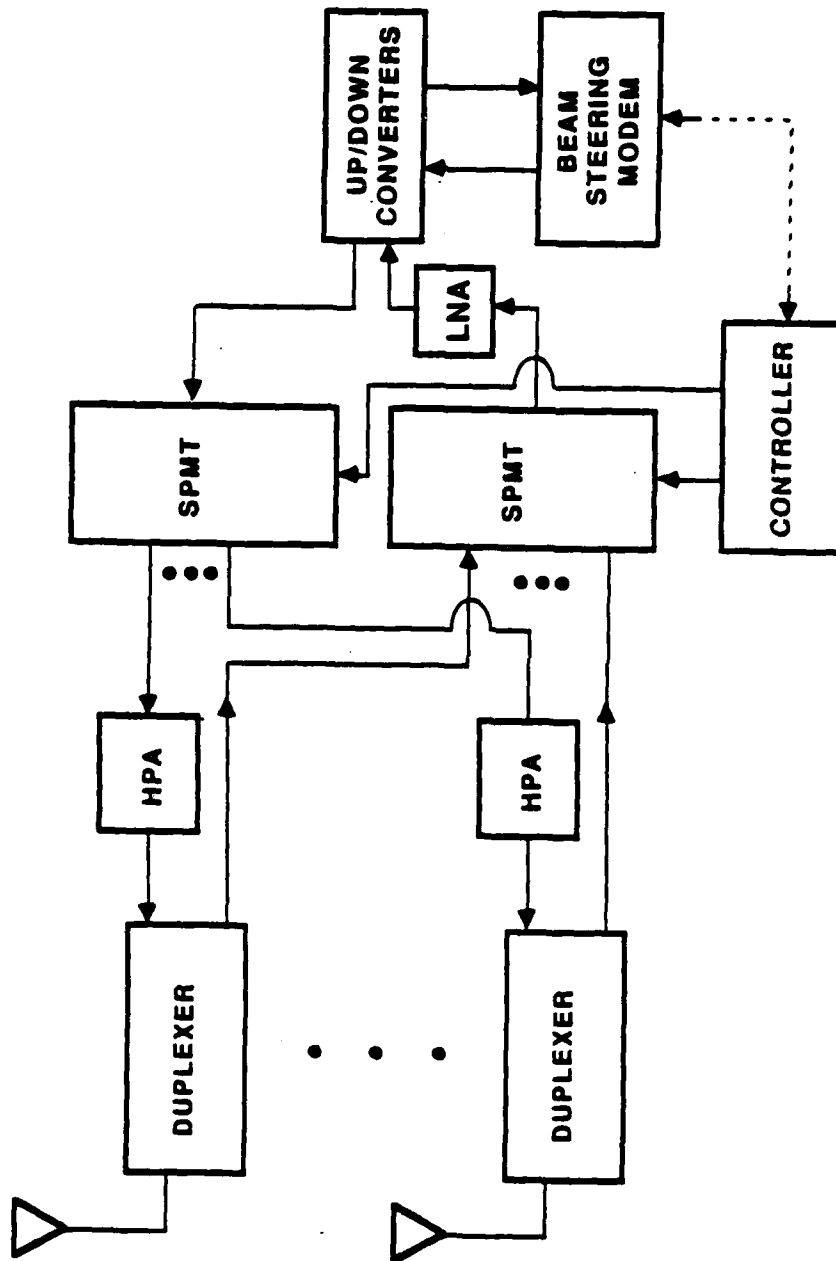


FIGURE 3 BLOCK DIAGRAM OF HYBRID CONFIGURATION

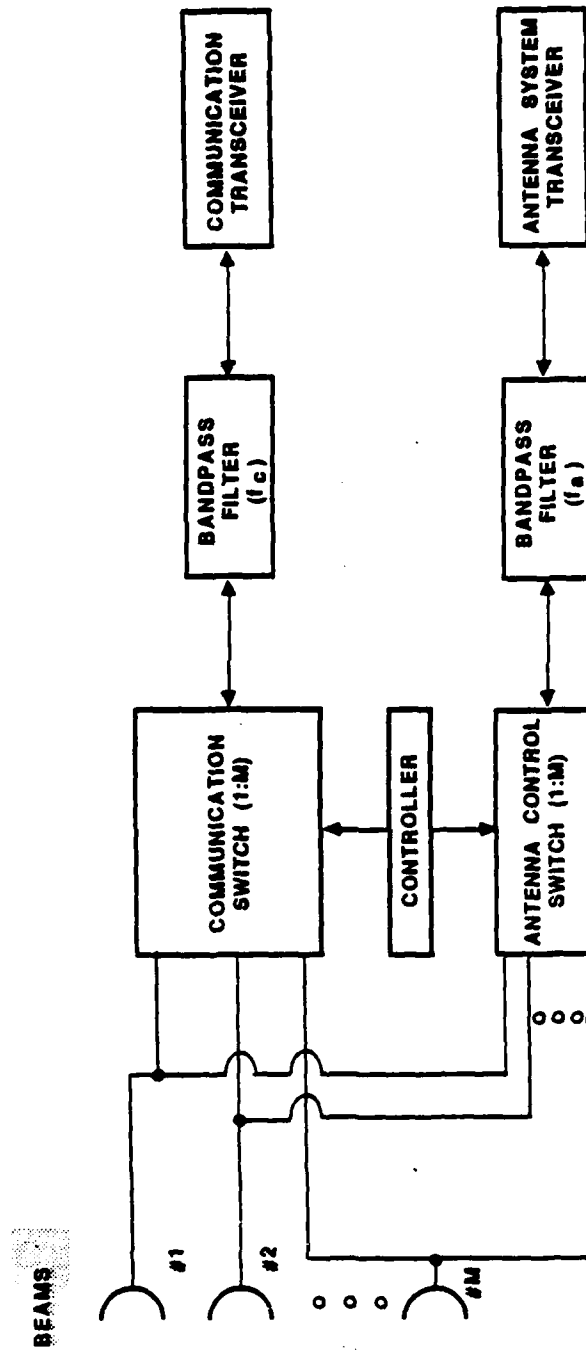


FIGURE 4 CONCEPTUAL BLOCK DIAGRAM OF PROPOSED TWO FREQUENCY
BAND ADAPTIVE BEAM SYSTEM

In some circumstances the 3 dB loss associated with the hybrids may be a worthwhile price to pay to separate the beam tracking and communication functions. For example, if the number of beams (M) is large and the number of users (N) is small using the beam acquisition frame for communication could result in an efficiency loss much greater than 3 dB. Thus, the hybrid loss could be acceptable since it permits much greater communication efficiency.

An alternative configuration is shown in Figure 5. The 3 dB hybrid loss is reduced to the diplexer loss which can be made as low as 0.5 dB. The configuration is not sensitive to the physical layout as was the T alternative of Figure 4. The principal disadvantage of this configuration is the requirement for M diplexers. Additionally, the beam steering signals encounter the sum of the losses of the diplexer, the SPMT switch, and the duplexer (both for transmit and receive).

Both configurations are shown under the assumption that the communication modem is time shared between different network nodes. In some circumstances separate continuously operating modems might be desired. In this case the communications SPMT switch would be replaced with a frequency multiplexer and a slower acting multipoint switching device for connecting the several communication modems to the proper beam.

If one were willing to constrain system operation such that data transmission was synchronized with (and in burst format) the beam steering signal, then it would be possible to use a single SPMT switch and a single diplexer greatly simplifying the system. However, this is a severe constraint to place on the communication system. A packet-switched system is probably the only compatible format. Synchronous TDMA systems such as a JTIDS while offering the required burst format have a framing structure and size that cannot readily be modified to match the parameters of the antenna beam steering system which will depend on the number of beams and the number of network nodes as well as implementation factors.

The block diagrams of both Figures 2 and 3 could be extended in several fashions to accommodate the communication function. None of the approaches is particularly attractive. Consider Figure 2. If diplexers were placed (between the up/down converters and the two SPMT switches the communication beam scanning pattern would be constrained to match the acquisition and tracking scanning pattern. This constraint

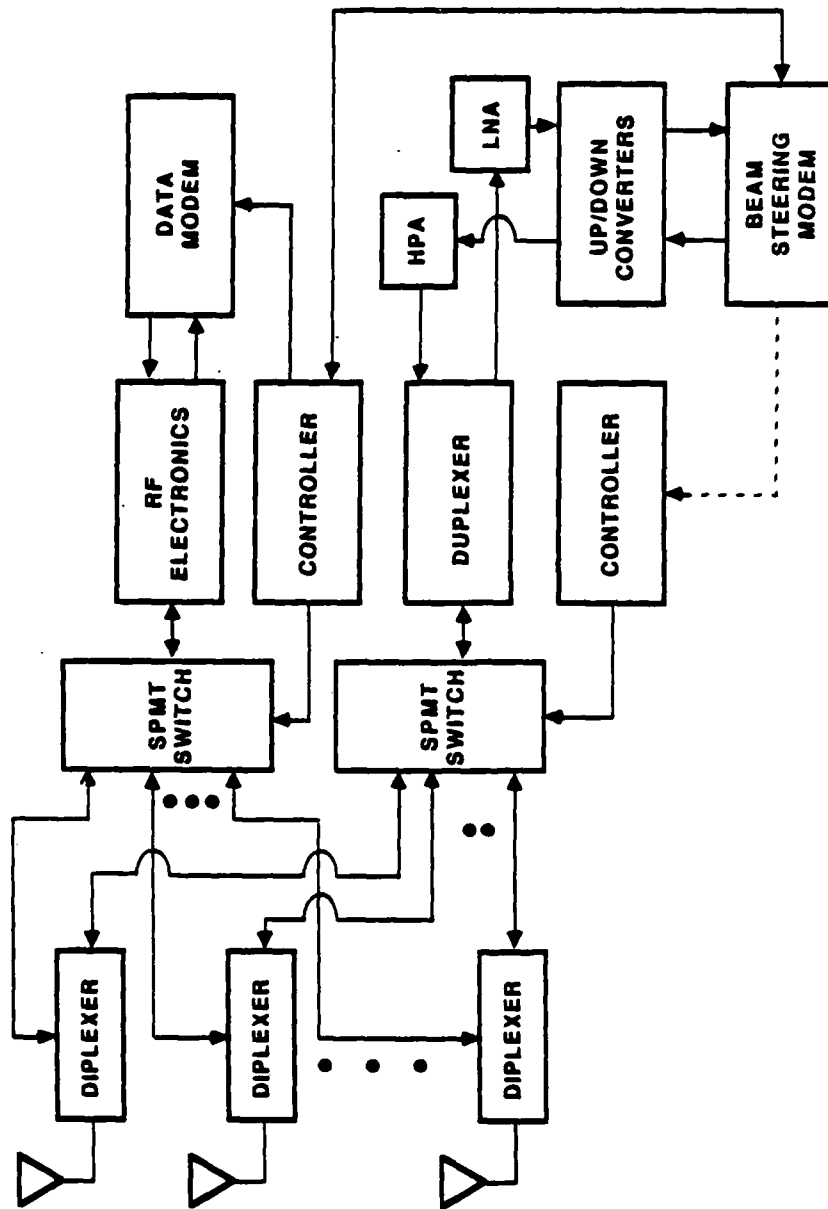


FIGURE 5 BLOCK DIAGRAM OF SIMPLEST ADAPTIVE BEAM CONFIGURATION ACCOMMODATING SEPARATE SCANNING PATTERNS FOR ACQUISITION AND TRACKING AND FOR COMMUNICATION

could be avoided by placing the diplexers between the antenna elements and the duplexer. Unfortunately, this approach is extremely complex requiring two sets of HPAs and LNAs for each of the antenna elements. Alternatively, the diplexers could be placed at the input to the HPAs and the output from the LNAs. In this case HPAs must be capable of operating in a linear mode so that IM cross products created by the two signals in a nonlinear amplifier do not create undesired interference. Thus, a significant power loss of 4 or 5 dB will result.

Similar problems arise when diplexers are introduced at various points in Figure 3. Consequently, under most circumstances the approach shown in Figure 5 is the preferred approach although the approach of Figure 4 might prove useful.

SECTION 3

SIGNAL DESIGN FOR THE ADAPTIVE BEAM SYSTEM

In principal, one could consider using the communication signal for the antenna beam steering function. In practice, the concept is impractical for several reasons. First, it is desirable to have an adaptive beam antenna system that operates independently of the selected communication modem. A single adaptive beam antenna system is much more desirable operationally than a system that must be modified for each and every modem with which it must operate.

Second, use of the communication modem signal may result in excessive acquisition time. This will certainly be the case if the communication signal is spread spectrum in a format requiring a long acquisition time. Pointing two planar antenna beams at each other represents a two-dimensional acquisition problem. Including the communication signal increases the dimensionality to at least third order and without proper care could result in a dramatically increased acquisition time.

Third, the requirements for antenna beam tracking and acquisition may do serious harm to the communication signal structure. For example, in order to achieve satisfactory antenna system performance it may be necessary to on/off gate the communication signal in such a fashion as to greatly degrade the communication system performance.

Fourth, it may not be desirable to operate the communication system in the same mode as the antenna system. For example, it is desirable in many cases to operate the antenna system as a true broadcast network where all users share a common transmit/receive frequency. However, the communication system may consist of a set of addressed point-to-point links rather than a true network. In such a case it is necessary to use a separate communication signal to achieve this point-to-point addressed capability.

For the reasons cited above we restrict our subsequent investigations to those adaptive beam antenna systems that use a dedicated signal designed to provide the beam steering function. Since there are two sets of signals that must share a common antenna system (use of separate antenna systems is judged to be too costly) it is necessary to select a

multiple access system to perform this diplexing operation. The three candidates are: 1) time-division multiple access (TDMA), 2) code-division multiple access (CDMA), and 3) frequency-division multiple access (FDMA).

TDMA can be ruled out as a practical technique since it forces a serious interaction with most communication signals which are not gated on and off but are continuously present. Furthermore, during beam acquisition (or net entry net) timing may not be available to permit TDMA operation. Thus, TDMA does not appear to be a practical multiple access technique for this application.

CDMA may be an effective technique depending on the details of the application. The disadvantage of CDMA is that it is not a truly orthogonal multiple access technique. However, if there is sufficient bandwidth the mutual interference can be made negligible. Nominally both the communication and antenna system signals would be in a spread spectrum format but CDMA diplexing could be achieved with only one of the signals being spread.

In an important sense CDMA is undesirable since one must be concerned with the interaction between the two signal sets in great detail. For example, with two frequency-hopping signal sets the spread spectrum processing gain may be adequately high but with slow hopping rates the errors may occur in undesirable bursts.

FDMA is the multiple access technique recommended for general application owing to its orthogonal character. The communication and antenna system signals can be created independently and differently. For example, FDMA sharing permits the antenna system signals to share a common transmit/receive channel with a gated time-variant beam pattern while the communication band is shared among all modems by a combination of FDMA and spatial beam sharing. In other words for the antenna system signal band the antenna beams would be scanned in time searching for new net entry signals while in the communication band static beam patterns could be established (perhaps as a function of frequency) thereby permitting conventional (100% duty factor) modems to be used. The major disadvantage with FDMA is the requirement for two frequency bands.

3.1 ANTENNA SYSTEM SIGNAL DESIGN

In previous sections it was determined that best architecture used a separate signal for beam steering of the antenna system and that it was preferable to use a separate frequency band for the beam steering signals. Under these assumptions we now consider the general character of the antenna system signal.

A common waveform should be used by all nodes so that it is possible to network these nodes. However, each node should contain as data the node serial number or identifier word. A spread spectrum waveform should be used to enhance the LPI performance and permit spread spectrum processing gain to be used against received interference.

The spread spectrum signal should be designed to have rapid acquisition characteristics since it is necessary to acquire quickly when the beams are aligned properly. For direct sequence (DS) spread spectrum signals matched-filter detection (by SAW matched filters or convolvers) is best while correlation detection is acceptable for frequency hopping (FH) spread spectrum if the hopping rate is slow enough and network timing is available to all nodes. Network timing could be provided by GPS receivers located at each node. In the case of DS spread spectrum modulation one should consider a fixed pattern as an initial design for demonstration purposes. For security reasons subsequent designs would change the "fixed" pattern as a function of time based on a pseudorandom pattern. Such a procedure would require network timing but the timing accuracy could be quite low since the rate of change of the code chip pattern could be quite low. SAW convolvers permit the code pattern to be changed quickly as a function of time. Convolvers are planned for use in the low cost packet radio network presently being developed by the U.S. Army CENCOMS and DARPA.

In summary, for most circumstances we recommend that the beam acquisition signals be a DS spread spectrum format using matched filter detection. A common code should be used for the entire network and this code should be changed periodically at a rate consistent with the security requirements.

SECTION 4

BEAM ACQUISITION ARCHITECTURES FOR LINK ESTABLISHMENT

In this section we consider the problem of establishing a link between two nodes. It is assumed that there are only two nodes. The beam acquisition architectures consist of the beam patterns and the beam search algorithm.

For this problem we make the following assumptions. One other node with identical characteristics is assumed to exist and to wish to communicate. The acquisition algorithms must treat both nodes as equals. That is, neither node may assume a master role. Full duplex transmission occurs with each node transmitting on a separate frequency. Thus, contention between the two transmitters cannot occur. The dwell time required to establish a connection between the nodes when both use their narrow beam antennas for transmit and receive is denoted T_d .

4.1 BEAM PATTERNS

There are two possibilities for beams: 1) omnidirectional beam (OB), and 2) narrow beam (NB). Since one must be concerned with both transmit and receive beams there are four possibilities. Our notation lists the transmit beam first and receive beam second. The first case is OB/OB and being the normal case used in tactical communication is not considered further here. The second case OB/NB uses an omnibeam for the transmit and a narrower beam for the receiver. The third case uses a narrower beam for the transmitter and an omnidirectional beam for the receiver. The final configuration, NB/NB, uses narrow beams for both transmission and reception.

The principal advantage of the omnidirectional transmit antenna beam configuration (OB/NB) is its simplification of the acquisition protocol. In addition, an immediate link (one-way) is established when one receive beam is pointed correctly. Unfortunately, a full duplex link requires that both receive beams are correctly pointed and a one-way link establishment does not help point the remaining receive beam - unless both nodes know their own location.

The principal disadvantages of the OB/NB configuration are: 1) the reduced link budget (assuming a constant transmit power), and 2) the poor LPI owing to the broadly radiated power, and 3) in general, more self-interference.

For the NB/OB configuration the principal advantages are: 1) simplified acquisition protocols, and 2) immediate establishment of a one-way link when the receive beam is properly pointed. The principal disadvantages are: 1) the reduced link budget, 2) the poor AJ performance owing to the broad receive pattern, and 3) in general, more self-interference.

For the NB/NB configuration the principal advantages are: 1) the enhanced link budget, 2) the better AJ performance, 3) the better LPI performance, and 4) in general, less self-interference. The major disadvantage of the NB/NB configuration is the two-dimensional search required for acquisition.

4.2 SEARCH ALGORITHMS

There are two major categories of search algorithms. In the first category a variable beam size is used while in the second category a fixed beam size is used for the acquisition process. (Although the beam size may change between the acquisition and tracking modes of operation). The variable beam size approach is most easily visualized as an approach in which one starts with an omnidirectional beam and progressively reduces the beam width as more is learned about the location of the other node. It will be shown that the variable beam approach offers no acquisition time improvement. Furthermore, the variable beam size approach is more complex to implement and encounters greater system difficulties in the network environment than the fixed beam size approach. As a result we concentrate our consideration on fixed beam size algorithm.

Owing to the advantages of the NB/NB configuration cited above we concentrate our consideration on two-dimensional search algorithms for this configuration. (It may be easily shown that the NB/NB beam pattern can acquire as rapidly as any other beam pattern since the increased number of search bins is exactly compensated by an increase in the received SNR.)

4.2.1 Selective Scan Algorithm

The selective scan algorithm is a very effective acquisition algorithm which does not require time synchronization between the nodes. Selective scanning was developed for selecting the carrier frequencies for HF sky wave communications through an uncertain sky-wave propagation channel. Here we extend the concept to angular position rather than the carrier frequency.

The principal difference between these two cases is that multiple frequencies might propagate at HF while only one angular position will work for LOS tactical communication.

With the selective scanning technique there are two possible scanning approaches. With the first approach the transmit beam completes one complete cycle while the receive beam dwells in one location. The receive beam then advances to a new location and the cycle repeats. With the second approach the receive beam completes one full cycle while the transmit beam remains fixed in one position. The transmit beam then advances to a new location and the cycle repeats. We recommend the first approach since a rapidly scanning transmit beam is harder for an unfriendly observer to detect.

4.2.2 Variable Beam Size Algorithm

The alternative scanning approach uses a variable beam size with the beam progressively narrowing at each stage. Since the dwell time is proportional to the beamwidth the time required to search all positions is independent of the beamwidth. Thus, under this criterion the amount of narrowing at each stage has no effect on performance. On the other hand, if one knows that the other node exists, a single test provides the needed information for the binary progression case. Under this assumption the binary reduction approach is the optimum reduction ratio for the variable beam size algorithm.* However, the variable dwell times and signaling rates would be very difficult to implement as compared to fixed beam size systems. The variable beam size algorithm can be applied to either the transmit or the receive beam or both.

* That is, if no signal is detected one is guaranteed that the other node must lie in the other beam position. Thus, there is no need to search that position. Different assumptions could lead to an optimal beam width reduction factor other than 2.

We now proceed to determine the link acquisition times for the three leading search algorithms for the 2-node link situation.

4.3 LINK ACQUISITION TIMES

4.3.1 Selective Scanning

It takes M dwell times to execute the transmit cycle and M transmit cycles to execute the receive cycle. Thus, a one-way link is established in a time $M^2 T_d$. Where T_d represents the dwell time required for reliable signal detection. Since the two one-way searches are conducted separately on different carriers a full duplex link is established within the same period of time.

4.3.2 Omnidirectional Transmit Beam - Binary Search of Receive Beams

With this algorithm it is only necessary to perform a search of the receive beam. In the first step the required dwell time is $M^2/2 T_d$ where a factor of M occurs owing to the omnidirectional transmit beam and a factor of $M/2$ owing to the semicircular receive beam. Assuming that M is a power of two, i.e., $M = 2^m$, the next step would be a quadrant test requiring a dwell time of $M^2/4 T_d$. Thus, the total time required to locate the transmit source to within one of the M beams is

$$M^2 T_d (1/2 + 1/4 + \dots + 1/M)$$

For M the expression within the parentheses is approximately one and this algorithm offers no acquisition time advantage over the selective scanning algorithm. Furthermore, the procedure of dwelling for progressively shorter times is operationally more complex than for the case of selective scanning of fixed narrow beams.

4.3.3 Binary Search of Both Transmit and Receive Beams

Since at each stage of the algorithm we are trying to gain two bits of information, it is necessary, in general, to try all four possible combinations.

At the first stage the required dwell time at each possibility is $(M^2/4)T_d$. since there are 4 combinations, the maximum time to narrow the link beam patterns by a factor of 2 is M^2T_d while the average time is $(M^2/2)T_d$. At the second stage the worst case and average times are $(M^2/4)T_d$ and $(M^2/8)T_d$, respectively.

Thus, the time required to reach the narrowest beam configuration for the worst and average cases is

$$M^2T_d \left(1 + \frac{1}{4} + \frac{1}{16} + \dots + \frac{1}{M}\right)$$

and

$$\frac{M^2T_d}{2} \left(1 + \frac{1}{4} + \frac{1}{16} + \frac{1}{64} + \dots + \frac{1}{M}\right), \text{ respectively,}$$

The expression within the parenthesis is less than 1.33. Comparing these results with the selective scanning algorithm we find that the present approach offers poorer performance. Furthermore, the two-dimensional binary search algorithm is more complex.

4.3.4 Summary

Our conclusion is that the use of the narrowest beams both for transmit and receive is the preferable approach, thus, selective scanning using the narrowest beams is the recommended approach. The desirability of this approach can quickly be established by the following argument which compares two beamwidths differing by a factor of two.

Consider the receive beams. The narrower beam has twice as many positions to search but owing to the greater antenna gain the dwell time may be reduced by a factor of 2 resulting in no difference in search time. However, the narrower beam search provides one more bit of information about the location of the other node and consequently is the better approach.

For the case of the transmit beams there are two cases that must be considered. In the first case, the transmit power is assumed to remain constant. In this case the EIRP is doubled with the narrower beam so that the dwell time may be reduced by a factor of 2

resulting in no net difference in acquisition time. However, the narrower beam is preferable since it provides an additional bit of information. In the case of constant EIRP there is no change in dwell time and as a result the narrower beam pattern takes twice as long to search as the broader beam. The increased acquisition time does yield an additional bit of angular resolution.

Considering complexity and link acquisition time we strongly recommend a beam acquisition architecture based on the NB/NB beam pattern using the selective scan search algorithm with rapid transmit scanning and slow receive scanning.

4.4 RANDOMIZATION OF THE SELECTIVE BEAM SCANNING ALGORITHM

In the previous section we described a selective beam scanning algorithm in which both the transmit and receive beams step in sequence through angular positions. In effect, a discrete angular rotation takes place. The disadvantage of this approach is that a predictable pattern of transmission and reception occurs thereby reducing the LPI and the interference and AJ immunity, respectively. Randomization of the transmit and receive scanning patterns can greatly improve the situation. Since every possible combination of beams is tried between every pair of nodes, it is possible to scramble the sequence of both transmit and receive beams differently at each node. Furthermore, the sequence can be changed from frame to frame independently at each node.

The only impact of this randomization is that the maximum beam acquisition time is increased from one frame to two frames. This worst case occurs when the appropriate alignment time is just missed at the beginning of one frame and owing to the scrambling the appropriate alignment time does not occur until the end of the following frame. Since the beam sequence may be changed independently at each node there is no requirement for time synchronization of the changes in the beam sequence.

4.5 STEADY-STATE TRACKING

Since many systems involve mobile nodes it is desirable to develop tracking algorithms as well as acquisition algorithms. This can be achieved best through the receive antenna system. Use of the transmit antenna system would result in unnecessary interference. Information obtained from the receive antenna system can be used to control the transmit antenna beam.

Since a MBA provides fixed beams, tracking can be generated by observing also the two contiguous beams (one on either side) and comparing the relative desired signal strength in each of the 3 beams.* With idealized beams (no overlap) the desired signal will be in one and only one beam. Depending on the signal structure either one or three receivers may be required. Practically it is desired to time share one receiver between the three beams. However, this is only possible if one tracks on the antenna tracking and acquisition signal - otherwise the communication signal would be degraded when the adjacent beams are being used. Since the beam acquisition algorithm attempts to receive the beam acquisition signal in each beam the output from the matched filter can be used to determine the correct beam once per acquisition frame.

With a practical MBA system the beams will not be ideal and it is desirable to design the beams to have considerable overlap so as to avoid non-covered angular regions. In this practical situation at least two, of the receive beams may contain significant energy. In this case the selected beam is simply the one with the maximum energy. If two beams have equal receive energy one simply randomly chooses between the two.

We recommend using the beam acquisition signal to provide the required steady-state tracking since this approach does not entail any disruption or degradation of the communication signal. A single modem (which is required for the beam acquisition function) is already time switched over all beams and thus, provides the required tracking information. For the case of only two nodes the beam acquisition search frame is sufficiently short that there is no difficulty in tracking rapidly moving nodes.

* Here we assume that the system is designed so that the fastest mobile node can only move from one beam to the adjacent beam in a tracking interval.

SECTION 5

ADAPTIVE BEAM ARCHITECTURES FOR NETWORKS

Designing the beam acquisition and tracking algorithms for a network environment is much more complex than for a simple 2-node point-to-point link. Even without antenna considerations networking is much more complex than a point-to-point link. Consider the complexity of the protocols associated with the packet radio network [Ref. 5-1]. Including an adaptive beam antenna system further complicates the protocols since it is necessary for this network to also support the following functions in the above environment; 1) beam acquisition, 2) steady-state beam scheduling, 3) beam tracking for mobile nodes, and 4) net entry for a new node entering an existing network.

5.1 MATHEMATICAL STATEMENT OF THE NETWORK PROBLEM

The purpose of the adaptive beam antenna system acquisition and tracking system is to provide at each node i ($i=1$ to N) the $(N-1)$ angles θ_{ij} ($j=1$ to N ; $j \neq i$) to the other $N-1$ network nodes.

Note that $\theta_{ij} + \theta_{ji} = \pi$ rads. In general, the network will not be fully connected, i.e., propagation conditions may prevent direct communication between a node pair. In this case it is not necessary or directly possible to estimate the two angles for every node pair.

Since in principle, $\theta_{ij} + \theta_{ji} = \pi$, it is necessary to estimate only one of the angles. However, it is desirable to treat each node identically and as a result the beam scanning algorithms should determine both angles. For the MBA systems under consideration the angular choices are discrete and the "estimation" process is a decision or hypothesis testing process.

The discrete estimate of the angles will be used to control the direction of the communication beams (which will most likely operate at a different frequency).

5.2 NETWORK ISSUES

Often it is desirable or necessary to operate in a net radio mode. That is, all users share the same transmit (and receive) frequency. Typically it is assumed that all users can receive each other since omnidirectional antennas are commonly employed. However, considerable concern has been addressed with "hidden" terminals in some radio networks such as the packet radio network [Ref. 5-1]. For our proposed adaptive beam antenna system virtually all terminals are hidden unless a specific attempt is made to point both transmit and receive antennas correctly. Thus, to achieve net operation the transmit antenna pattern must have lobes simultaneously or sequentially pointed at each network node. The same criterion must apply to each receive antenna as well.

Use of simultaneous lobes greatly simplifies the scheduling problem but permits network self interference (or network intrinsic noise) to limit performance. By contrast, use of sequential beams can largely avoid network intrinsic noise. However, a significant scheduling problem can result as is subsequently discussed.

If one assumes that there are N nodes requiring full mesh connectivity then there must be at least $N(N-1)/2$ slots if the beam patterns are scheduled serially in time sequence.* Since an antenna beam is shared for transmitting and receiving it is necessary to further subdivide this slot into subslots allowing each node a turn to transmit and receive. If one assumes that network timing is available, then two subslots are sufficient. However, if one assumes that network timing is not available, then, in general, four subslots are required. Thus, for a N node network full connectivity requires $N(N-1)$ and $2N(N-1)$ subslots in its frame structure for synchronized and unsynchronized networks, respectively. However, in a typical scheduled environment synchronization would exist (after net entry) and the smaller number would be the applicable value. Table 5-1 presents the frame duration for several assumed subslot durations as a function of the number of network nodes if only one pair is permitted to communicate at a time.**

* Many of these slots may use the same beams. Furthermore, since the beams may be different parallel scheduling is possible, in general.

** Needless to say, this is a pessimistic assumption corresponding to the worst possible case.

TABLE 5-1

**FRAME DURATIONS FOR N NODE MESH NETWORK
(SYNCHRONIZED NETWORK)**

<u>SUBSLOT DURATION (ms)</u>	1	10	100
<u>N</u>	<u>T_F(ms)</u>	<u>T_F(s)</u>	<u>T_F(s)</u>
5	20	0.2	2
10	90	0.9	9
20	380	3.8	38
50	2450	24.5	245

Table 5-1 demonstrates that long frame durations can occur for even modest size networks if full mesh connectivity is required. Typically in tactical situations one requires transmission opportunities to occur quite frequently. For example, one opportunity per 10 seconds represents an upper bound given message delay requirements. In this case the subslot duration should be 10 ms or less if one desires to support a reasonable number of network nodes. The electromechanical switches are unacceptable - at least under these worst case assumptions.

The minimum subslot size is set by several factors. First, the beam switching time is a very important factor. Electronic beam switching at modest power levels can be achieved in a few microseconds or less. Electromechanical beam switching requires a few tens of milliseconds. Thus, larger networks with rapid message delivery requirements must use electronic beam switching. The subslot size is also determined by the burst data rate, the baseband channel rate, and propagation delays. The subslot duration must be able to support the required baseband channel rate if the same frame structure is used for beam acquisition and communication. The lower the burst rate the longer the subslot. The required receiver acquisition time also affects the subslot size.

Thus, receiver techniques that require particularly short acquisition times are desirable since they reduce subslot and frame duration thereby increasing communications efficiency and decreasing message delay. Finally, the minimum subslot size is affected by the propagation delays between the network nodes. Under some circumstances these may be as high as 2 or 3 ms.

Independent of antenna considerations it is necessary for net operation to share a common frequency for transmission and reception. Without network synchronization one requires a method of sharing the frequency between two nodes such that full duplex transmission is possible. An effective approach using two Walsh functions requires only 4 subslots.* Once net synchronization is achieved it is possible to share the channel with 100% efficiency using only two subslots. However, in the initial acquisition phase of network timing the four subslot approach is required to guarantee a 2-way connection.

5.3 NETWORK PROBLEMS WITH VARIABLE BEAM SIZE ALGORITHMS

In a network environment the variable beam algorithms encounter significant problems. The first and most obvious problem is that the broader beams used in the early stages of the acquisition process are very likely to encounter occupancy by multiple nodes creating contention and interference. While this potential contention can be accommodated by developing appropriate T/R sequences their length grows rapidly with the number of nodes.

In addition, finding a desired node in one of the two beams does not preclude the possibility of other nodes lying in the other beam. Thus, in general all beams positions must be searched.** Clearly, if followed, this procedure requires more time than simply exhaustively searching all the narrowest beams.

An alternative approach is to search for each network node separately and in sequence. Such an approach requires N times longer than a pairwise link acquisition. Furthermore, the network problem is further complicated by the need to establish which two nodes are

* While absolute time base synchronization is not assumed, the Walsh function approach does assume that the clock rates (if not phases) are closely synchronized.

** If $N < M$ it may be possible to reduce the search time substantially.

trying to establish a link at a time. The scheduling algorithm must avoid one node attempting to link with two or more nodes simultaneously.

In summary, a beam acquisition technique based on progressively narrowing the beam width is undesirable for a network environment.

5.4 SELECTIVE SCAN ALGORITHM FOR NETWORKS

The selective scan algorithm uses a separate scanning pattern for the transmit and receive beam. Each network node uses a similar scanning pair except that: 1) there may be a time base offset between the various nodes and 2) the beam sequence may differ. It is assumed that scanning frequencies are either synchronized precisely or they are sufficiently stable and the dwell time is more than adequate to permit detection within one half of its duration.

With the recommended selective scanning algorithm the transmitter beam at each node cycles through all M beam position in one receive beam dwell time. While the inverse procedure could be used with equal acquisition efficiency it would result in degraded LPI performance. Since there are M beam positions the total cycle time for each node is PM^2 transmit dwell times where P is an integer that will be discussed below. Within this period each node pair that is within LOS connection can establish communication. However, the link connection between a node pair will not be simultaneous. In general, it is necessary to wait the full PM^2 dwell times before full duplex communication is established. In some circumstances this delay may be unacceptable and an immediate duplex connection required - see the following sections.

We now present a T/R cycle which guarantees link establishment once the two beams are aligned given the potential transmit/receive conflicts between N unsynchronized users. Consider the i -th and j -th nodes attempting to establish a link. Assume that linkage can occur when the beam positions of the i -th and j -th nodes, respectively, are $i=\alpha$ and $j=\beta$. A one-way link between the i -th and j -th nodes will be established when $(T_i=1, i=\alpha)$ and $(R_j=1, j=\beta)$. Similarly, a one-way link will be established between the j -th and i -th nodes when $(T_j=1, j=\beta)$ and $(R_i=1, i=\alpha)$. $T_k=1$ indicates that the k -th node is transmitting while $T_k=0$ indicates that no transmission is taking place. Since, in a true net operation, a

common transmit and receive frequency is used, one must realistically assume that it is not possible to transmit and receive simultaneously. Furthermore it is clear that one should attempt to receive whenever one is not transmitting.

Thus, when the two beams are pointed at each other (most likely a transmit beam at a receive beam but with low probability both transmit and receive beams), it is necessary to develop transmit/receive cycle patterns for each node such that communication in both directions is possible. Each node will require a unique T/R cycle pattern of period P which satisfies the condition that during this period there are instants when $T_i=1$ and $R_j=1$ and $T_j=1$ and $R_i=1$ for each pair (i,j) in the network.

A set of functions with the desired properties under time shift uncertainty can be based on square waves of various frequencies, that is, subsets of Walsh functions. The set is formed starting with the highest frequency square wave, halving the frequency and using two components shifted by 90° , halving this frequency and using two components shifted by 90° , etc. The result is that

$$P = 2^{(N+1)/2}$$

For each increase in the number of nodes by 2 the sequence length doubles.

Thus, we see that to accommodate a network of N unsynchronized nodes the beam dwell time must be increased by the factor P in order to accommodate the transmit/receive combinations between all network nodes. Thus, selective scanning in a network environment is much more complex and requires much more time than for the case of simple link establishment where two carrier frequencies may be used.

Table 5-2 presents the sequence period as measured in dwell times for a range of values of N . From this table we can see that the required frame time (measured in dwell times) can be quite large even for a small number of nodes. For example, even with only a 1 ms

TABLE 5-2

TRANSMIT/RECEIVE SEQUENCE PERIOD (P) AS A
FUNCTION OF THE NUMBER OF NODES

<u>NUMBER OF NETWORK NODES (N)</u>	<u>SEQUENCE PERIOD (P)</u>
3	4
5	8
7	16
9	32
11	64
.	
.	
.	
25	8,192
.	
.	
.	
51	$6.7 \cdot 10^7$

dwelt time, 8 beam positions, and 11 nodes the network cycle time of 4.06 seconds is required. In summary, the worst case network synchronization time is $2^{(N+1)/2} \cdot M^2$ dwelt times.

An alternative procedure is to use a probabilistic transmission approach. The scheme described above guarantees connection within the specified time. A probabilistic approach cannot guarantee connection but may result in a reduced average acquisition time or an increased probability of acquisition within a given time period. Assuming independent transmission and reception decisions at each node the probability of success in any one trial is 1/4. Given n such trials the probability of success is given by

$$\sum_{i=1}^n \binom{n}{i} p^i (1-p)^{n-i}$$

where $P=1/4$. Alternatively, the probability of success is given by 1 - probability of failure or

$$\begin{aligned} & 1 - \binom{n}{0} p^0 (1-p)^n \\ &= 1 - (1-p)^n \\ &= 1 - (3/4)^n \end{aligned}$$

For example, ten random trials will result in a 94.37% chance of successful linking in a one-way direction. Thus the probabilistic trial method may be preferred for a network with a large number of nodes.

In summary, when applied to a network environment the selective scanning algorithm is cumbersome and may require a lengthy beam acquisition frame structure. Worse yet, since separate transmit and receive beam scanning patterns are used the beam switching equipment is complex and costly. We next consider algorithms that use the same beam scanning patterns for transmit and receive.

5.5 RELATIVELY PRIME PERIOD SCANNING

The previous section discussed a net entry beam scanning procedure that guaranteed duplex access within one frame duration under worst case circumstances with respect to node location. However, under some circumstances it may be desirable to permit two-way communication immediately on alignment of the transmit and receive beams. (Note that with the selective scanning algorithm the transmit and receive beam search patterns are different so that duplex communication is not possible immediately upon establishing a successful simplex link.) Immediate duplex communication results by having each node use the same scanning beam pattern for transmit and receive. It is necessary to develop such a scanning algorithm that searches through all possible beam arrangement between all node pairs in a network.

One way of obtaining this goal is to make sure that each beam sweeps at a different rate from all the others. The beam angular scanning rate for the recommended MBA approach is discrete with a fixed dwell time in each beam position. Thus, there is a maximum scan rate or a minimum frame duration. Other scan rates are obtained simply by increasing the frame duration by an integer number of dwell times.* In order to guarantee that all beam pattern combinations are tried the periods (measured in dwell times) must be relatively prime between each and every pair of nodes. This constraint can result in some extremely long network frame durations (the product of each of the beam frame times) as the following example will illustrate.

Consider the case of a beam MBA circular pattern. Table 5-3 presents the frame times (measured in dwell times) for each node and the composite network frame time as a function of the number of nodes in the network.** Clearly, the network frame durations, i.e., the time required to guarantee a connection between any two nodes, becomes excessively large for even a relatively small number of nodes. Fortunately, an algorithm can be found that requires less time and provides immediate duplex communication. The next section describes in detail this very efficient network beam scanning algorithm.

* The additional dwell times could be a dead time, or could be used to repeat scans of certain most probable locations, or could be used to form an omnidirectional pattern for monitoring purposes.

** Here we ignore the potential transmit/receive conflicts in the network. The beam dwell time would have to be increased to accommodate these conflicts as described in the previous section.

TABLE 5-3

NETWORK FRAME TIME AS A FUNCTION OF THE NUMBER OF NODES N
FOR A 4 BEAM ANTENNA

<u>NUMBER OF NODES</u>	<u>ADDITIONAL FRAME PERIODS (BEAM DWELL TIMES BEAM)</u>	<u>COMPOSITE PERIOD (BEAM DWELL TIMES) PERIOD</u>
2	4,5	20
3	7	140
4	9	1,260
5	11	13,860
6	13	180,180
7	17	3,063,060
8	19	$38.198.10^6$
9	23	$1.3.10^9$
10	29	$3.9.10^{10}$

5.6 LATIN SQUARES SCANNING

Use of Latin squares scanning permits one efficient scanning sequence cycle for both transmit and receive [Refs. 5-2 and 5-3]. A Latin square of order 5 is shown in Figure 6. In this example the 5 integers correspond to five beam positions. Each column corresponds to a time sample with time progressing from left to right. Each row corresponds to a subframe of the scanning frame with time progressing from top to bottom. Thus, the scanning frame in this example consists of 25 beam dwell times - the sequence obtained by reading the square as one reads a page. Other nodes would have different Latin squares and scanning sequences. For the shortest scanning frame between two nodes their Latin squares must be orthogonal. That is, the ordered pairs of $(S, S') = (s_{ij}, s'_{ij})$ must have the property that each of the M^2 possible ordered pairs appears exactly once in the $M \times M$ array.

$$S = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 5 & 1 & 2 & 3 & 4 \\ 4 & 5 & 1 & 2 & 3 \\ 3 & 4 & 5 & 1 & 2 \\ 2 & 3 & 4 & 5 & 1 \end{bmatrix}$$

FIGURE 6 A LATIN SQUARE OF ORDER 5



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It is a well known fact based on Galois field theory that if M is a power of a prime, i.e., $M = P^a$, then there is a set of $M-1$ pairwise orthogonal Latin squares of order M . For our application M corresponds to the number of beam positions and the result states that the optimally compact beam scanning cycle can be found for a network consisting of up to $M-1$ nodes.

Figure 7 presents a table of some values of M that meet the above criterion. The most practical values are powers of 2 limited to $M=64$ or lower. Cost, size, complexity and weight will tend to keep the value of M low. On the other hand the larger M the larger the number of network nodes that can be supported with the most compact scanning frame. Subsequently, we will develop a technique for increasing N for a fixed M .

The Latin square scanning approach is highly desirable but does require time synchronization between all participating nodes. Depending on the dwell time this may not present a significant problem. Even with very short dwell times a GPS receiver at each node could provide the required time synchronization.

However, if the proposed application does not permit time synchronization then the Latin square approach is unacceptable unless appropriate modifications can be made to permit the entry of an unsynchronized node into an existing network. Later in this section we describe an effective technique for permitting unsynchronized net entry with Latin square scanning.

5.6.1 Increasing the Number of Network Nodes for Latin Square Scanning

In the previous section we found that for a compact scanning frame the number of network nodes is limited to $M-1$.^{*} Practical implementation factors may dictate that M is quite small. Consequently, it is desirable to find scanning algorithms that permit a greater number of network nodes. It is not necessary that these algorithms produce the most compact scanning frame. However, it is very important that the scanning frame be short.

* If one augments the $M-1$ orthogonal Latin squares with the cyclic enumeration square of order M (not a Latin square) the number of network nodes can be increased to M .

$M = p^a$ WHERE p IS PRIME

		POWER					
PRIME	$\begin{array}{c c} p & a \end{array}$	1	2	3	4	5	6
	1	1	1	1	1	1	1
	2	2	4	8	16	32	64
	3	3	9	27	81		
	5	5	25	125			
	7	7	49				
	11	11	121				
	13	13					

FIGURE 7 SOME VALUES OF M THAT PERMIT COMPACT SCANNING FRAMES FOR $M - 1$ NETWORK NODES



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One straightforward approach for increasing the number of nodes merely doubles the scanning frame while squaring the maximum number of network nodes. With this approach each Latin square is used by r network nodes where $r \leq M-1$. In general, these networks will be unable to communicate with each other in this subframe. However, in the next subframe each of the r nodes is assigned a different Latin square so that they can communicate in the second subframe. Thus, $(M-1)^2$ network nodes are guaranteed to have antenna alignment within $2M^2$ dwell times. Table 5-4 presents the number of supportable network nodes and the scanning frame times (measured in dwell times) for some representative values of M .

TABLE 5-4
MAXIMUM NUMBER OF SUPPORTABLE NETWORK NODES USING THE
DOUBLE FRAME ASSIGNMENT APPROACH

NUMBER OF BEAM POSITIONS (M)	NUMBER OF NETWORK NODES	SCANNING FRAME TIME
4	9	32
8	49	128
16	225	512
32	961	2048
64	3,969	8,192

Mathematically, the technique may be expressed as follows. The network nodes are grouped in $M-1$ elements and described as a set of $M-1$ vectors each of which has $M-1$ elements each of which is a 2-tuple of Latin squares.

$$\underline{R}_i = \begin{pmatrix} R_{0,i} \\ \vdots \\ R_{M-2,i} \end{pmatrix} \text{ for } i = 0 \text{ to } M-2$$

where

$$R_{i,j} = (S_i, S_{i \oplus j}) \text{ for } i, j = 0 \text{ to } M-1$$

and where S_i (for $i = 0$ to $M-1$) corresponds to the set of orthogonal Latin squares. The notation \oplus indicates addition modulo- $M-1$.

It may be readily seen that the all possible beam arrangements are tested and that the collection of R_i vectors (or the matrix created from the R_i vectors) consists of $(M-1)^2$ elements (network nodes) of two-tuples of Latin squares. Each Latin square corresponds to a scan of M^2 dwell times so that the total scanning frame duration is $2M^2$ dwell times.

We expect that the number of supportable nodes by the double assignment technique to be adequate for most applications. However, if there are a large number of nodes and/or the number of beams is small it may be necessary to extend the technique to a three-tuple of Latin squares thereby tripling the scanning frame duration and increasing the number of supportable nodes to $(M-1)^3$. For example, for the case of 4 beams it is possible to support 27 nodes and if a four-tuple of Latin squares were used 81 nodes could be supported.

5.6.2 Example of a Scanning System Design Based on Latin Squares

Assume that we have a four beam antenna system with beams described by the integers 0, 1, 2 and 3 corresponding to the four quadrants. Such a system might be implemented in a variety of fashions. For example, at low frequencies the antenna constellation might consist of 4 corner reflectors excited by a vertical monopole. Table 5-5 lists three orthogonal Latin squares that serve as the basis for beam scanning at three network nodes.* The scan is accomplished by reading each row from left to right and rows from top to bottom in the manner of reading a page.

If one wishes to support as many as 27 network nodes and guarantee a connection (assuming connectivity is possible from a propagation viewpoint) then it is necessary to use three successive Latin squares. Each of the 27 nodes is assigned a unique sequence of three Latin squares $S_i S_j S_k$. Since each sequence is unique each will differ from every other sequence in at least one of the three positions. Since the Latin squares differ and

* A procedure for generating orthogonal Latin squares is given by Bose and Manvel [Ref. 5-3] pp 135-144.

come from an orthogonal set all possible beam positions are tried between each pair of network nodes. Thus, 27 network nodes are supported within a scanning frame of 48 dwell times.

If a larger number of networks nodes were desired, e.g., up to 81, each network node would be assigned a unique sequence of four Latin squares $S_1 S_2 S_3 S_4$. These 81 nodes could be supported within 64 dwell times. Clearly, this chaining procedure can be used to support any number of network nodes - but with an increasing scanning frame duration.

TABLE 5-5

LATIN SQUARES USED TO CREATE EFFECTIVE BEAM SCANNING ALGORITHMS

S_1	S_2	S_3
0123	0123	0123
1032	2301	3210
2301	3210	1032
3210	1032	2301

5.6.3 Net Entry Algorithm

As noted above if the Latin square algorithm is to guarantee connectivity between all nodes these nodes must have time synchronization. In general, a net entrant lacks this synchronization and it is necessary to devise an enhanced algorithm that supports net entry for such a user.

We now describe a net entry algorithm based on the selective scanning algorithm that will guarantee unsynchronized connections with active net participants using Latin squares scanning. Thus, a hybrid overall system results. The net participants execute Latin square scanning while the net entrant(s) executes a modification of the selective scanning algorithm. The modification is very significant since it not only guarantees connections (if physically possible) but minimizes equipment complexity since the same scanning sequence is used for transmit and receive.

With this modified selective scanning the net entrant transmit and receive beams remain in one of the M positions for long enough that the network nodes have scanned through two sequences of M beam positions, that is, for the duration of two rows of the M by M Latin square. The total cycle time is 2 MxM dwell time or twice as long as with Latin square scanning. The doubling results since it is desired to try all possible beam combinations without time synchronization. Doubling the duration of the net entrant dwell times guarantees that all combinations are tried. The active network nodes transmit network TOD information permitting the net entrant to immediately achieve network timing once a beam connection has been established.

The proposed approach can be best understood by example. For simplicity consider the case of only 3 beams. There are two orthogonal Latin squares plus the cyclic enumeration square (which is orthogonal to the two Latin squares) shown last in Table 5-7. The selective scanning squares are shown in Table 5-8. Note that two 3x3 selective scanning squares are required since each row must be repeated once due to the lack of time synchronization between the active network and the net entrant. A net entrant would continuously sequence through these two squares until a link was established with the network and network TOD information was transferred to the net entrant permitting accurate network synchronization.

TABLE 5-7

THREE ORTHOGONAL SQUARES OF DIMENSION THREE

012	012	012
201	120	012
120	201	012

TABLE 5-8

SELECTIVE SCANNING DOUBLE SQUARE OF DIMENSION THREE

000	111
000	222
111	222

It should be noted that net entry must take place on a nonsynchronized basis using a common radio frequency. Thus, the entry protocol must be able to deal with the transmit/receive (T/R) contention between the two nodes. One effective method of dealing with this unsynchronized contention is to have two different T/R cycles. Active (and synchronized) net participants use the cycle TRTR while net entrants use the slower cycle TTRR. With this structure all four possibilities occur independent of cyclic shifts (produced by the net entrant's time base error) and, consequently, one is assured that both the TR and RT possibilities necessary for net entry occur.

An alternative approach to obtaining the required timing is to use a separate system to provide timing. GPS is a very attractive approach since the receivers are quite small and accuracy to a few tenths of microseconds is readily achieved. The disadvantage with this approach is the requirement for separate equipment. The advantage is that network timing is achieved without requiring transmissions that might reduce the system LPI capability. Of course, geographical considerations and switching speeds would limit how small the beam dwell time could be. In fact, propagation delays could in practical networks will cause substantially larger errors than those produced by a GPS receiver. Nevertheless, the GPS receiver is useful in reducing the magnitude of the time uncertainty for a net entrant.

5.6.4 Randomization of Network Scanning Patterns

In the preceding sections we found that the best approach is based on Latin square scanning with the net entrant using a modified version of selective scanning. The resultant structure therefore has a repetitive periodic scanning structure that is undesirable from a LPI point of view.

There are two methods whereby the periodic scanning structure can be made aperiodic yet the desirable properties of Latin square scanning maintained. With the first approach a pseudorandom integer (in the range 0 to $M-1$) is added to each scanning sequence value (modulo- M) producing a new scanning sequence. Since the same pseudorandom integer is employed by the entire network the desired orthogonality is maintained. The addition of the pseudorandom integer could also be applied to the net entrants selective scanning pattern if so desired.

The pseudo-random integer should be held fixed for the duration of at least one beam acquisition frame durations if connectivity is to be guaranteed. Much less frequent changes are recommended since it is necessary that all network nodes use the same pseudorandom integer. Lack of precise time base synchronization between network nodes may cause some brief transient intervals of lack of connectivity after each change of the pseudorandom integer. Nominally, one may consider that the pseudorandom integer changes a few times a second.

It should be noted that the net entrant scanning sequence need not use the pseudorandom integer. Even if the net entrant uses the wrong pseudorandom integer a connection can still take place owing to the exhaustive nature of the selective scanning procedure. Thus, net entrants do not need to have a synchronized time base for the pseudorandom integer. Once entering the network they will acquire network time synchronization and can therefore synchronize their pseudorandom integer generator as required for net participants.

A closely related, but different, second approach periodically interchanges the Latin square sequences amongst the network nodes. This approach encounters the same network synchronization problems described above.

5.6.5 Summary

We recommend the hybrid Latin square selective scanning approach described above. With this approach the net entrant cycles through the beams at a low rate using the selective scanning technique while the active net participants cycle through using a scanning sequence defined by their Latin square or sequence of Latin squares. This net entry procedure is clearly the most robust approach and does not rely on external equipment or timing.

5.7 NETWORK NODE TRACKING

Node tracking in a network environment can be best accomplished using the beam acquisition signals as recommended for the two-node link situation. Each beam location is sampled once per frame and the relative signal strengths determine the selected beam location. Observation of the time histories of signal strengths in each beam location could be used to estimate the angular velocity.

The same techniques are directly applicable to the network environment. However, in this case it is necessary to recognize that there are multiple nodes and multiple signals. Thus, the measured signal strengths (of the beam acquisition signals) must be associated with the corresponding node. This can be done since the spread spectrum beam acquisition signals carry as data the node identifier word.

It should be noted that collisions are possible between beam acquisition signal bursts when two or more nodes occupy the same beam position. Owing to the use of different Latin square beam scanning sequences a simultaneous transmission and resultant collision is relative unlikely. However, it may occur and it is desirable to develop a mechanism that prevents permanent contention and lockout. One simple approach oversizes the beam dwell times and then randomizes the time of transmission from one frame to the next. Alternatively, one could periodically interchange scanning sequences among all nodes so that permanent lockups were avoided. We recommend this latter approach since it is desirable to change the scanning sequence periodically for reasons previously discussed.

SECTION 6

SCHEDULING OF COMMUNICATION BEAMS IN A NETWORK

The previous section developed an efficient algorithm for beam acquisition in a network environment.

This beam pattern could be used to provide communication also but the desired level of efficiency may not be achievable. We examine this issue in greater detail in this section.

Our considerations assume that in the network environment it is desirable to time share a single modem for communication with other nodes. If separate FDMA links and modems were used for each communication link the issue of beam scheduling would not arise.

6.1 COMPACT BEAM SCHEDULING FOR STEADY STATE COMMUNICATION OPERATION

Assume a network of N nodes each geographically situated so that only one node is in a beam of each of the other nodes. Further assume that full duplex communication is desired with full mesh connectivity. Define a standard time slot as being able to support two-way communication. It is desired to determine the minimum frame duration (as measured in standard time slots) that will support this mode of operation.

There are $N(N-1)/2$ beam configurations required to support this mode of operation. If the network could support only one beam pattern at a time the frame duration would consist of $N(N-1)/2$ time slots each of adequate duration to permit full duplex communication. However, $N/2$ beam patterns may be formed simultaneously. As a result the required frame duration may be shortened substantially. In fact, for N even one can satisfy full net connectivity with only $N-1$ time slots. For N odd N time slots are required - some of which are wasted. Tables 6-1 and 6-2 illustrate examples for $N=4$ and 5.

TABLE 6-1

BEAM TIME PLAN FOR A 4 NODE NETWORK
(ENTRY SHOWS WHERE TRANSMIT BEAM IS POINTED)

<u>NODE NUMBER</u>	TIME SLOT NUMBER		
	<u>1</u>	<u>2</u>	<u>3</u>
1	2	3	4
2	1	4	3
3	4	1	2
4	3	2	1

TABLE 6-2

BEAM TIME PLAN FOR A 5 NODE NETWORK
(ENTRY SHOWS WHERE TRANSMIT BEAM IS POINTED)

<u>NODE NUMBER</u>	TIME SLOT NUMBER				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
1	2	3	4	5	
2	1	5		4	3
3	4	1	5		2
4	3		1	2	5
5		2	3	1	4

6.2 MOST COMPACT SCANNING AND FRAME DOUBLING LATIN SCANNING

Consider the case of two beams, i.e., $M=2$. Table 6-3 presents the Latin and cyclic enumeration squares which are orthogonal.

TABLE 6-3

2 DIMENSIONAL ORTHOGONAL SCANNING SQUARES

NODE	A	B
SQUARE	01	01
	10	01

Suppose that it is desired to double the number of network nodes. The question is what is the most compact scanning pattern that will support 4 nodes? There are 16 possible combinations of 4 binary variables. However, it is not necessary to execute all 16 possibilities to establish all pairwise links.

The frame doubling technique recommended in Section 5.6.1 uses only 8 dwell times to establish all possible pairwise links. Table 6-4 illustrates that the frame doubling technique achieves the desired goal in 8 dwell times.

TABLE 6-4

DOUBLE FRAME APPROACH TO DOUBLING THE NUMBER OF NETWORK NODES

<u>NODE</u>	<u>SCANNING SEQUENCE</u>
A	0 1 1 0 1 1 1 0
B	0 1 0 1 0 1 0 1
C	0 1 1 0 0 1 0 1
D	0 1 0 1 0 1 1 0

The scanning sequences of Table 6-4 are created by "reading" the squares of Table 6-3 in the same fashion as one reads a textbook. That is, each line is read from left to right and the page from top (row) to bottom (row).

The frame doubling approach (or multiplying approach, in general) does not lead to the most compact scanning sequence. Table 6-5 demonstrates that all possible pairwise links can be established in 5 dwell times. The fact that these scans establish all possible links can be more easily seen by the graph of Figure 8. The edges of the graph denote the pairwise links between the network nodes. The entries are the beam configuration followed by the time of occurrence (in parenthesis). From Figure 8 one can see that all possible beam configurations occur for each pairwise link.

TABLE 6-5

MINIMUM FRAME DURATION SCANNING SEQUENCES

<u>NODE</u>	<u>SCANNING SEQUENCE</u>
A	0 1 1 0 1
B	0 1 0 1 0
C	0 0 1 1 0
D	0 0 0 1 1

6.3 COMMUNICATION EFFICIENCY ESTIMATES FOR LATIN SQUARE BEAM SCHEDULING

It is clearly desirable to use a common scanning pattern to accomplish both the beam acquisition and the communication functions since this simplifies the equipment requirement. In general the communication scanning pattern will be shorter and more efficiently used but will skip certain directions of arrival and as a result may prevent net entry. The acquisition scanning pattern, while capable of accommodating a net entry

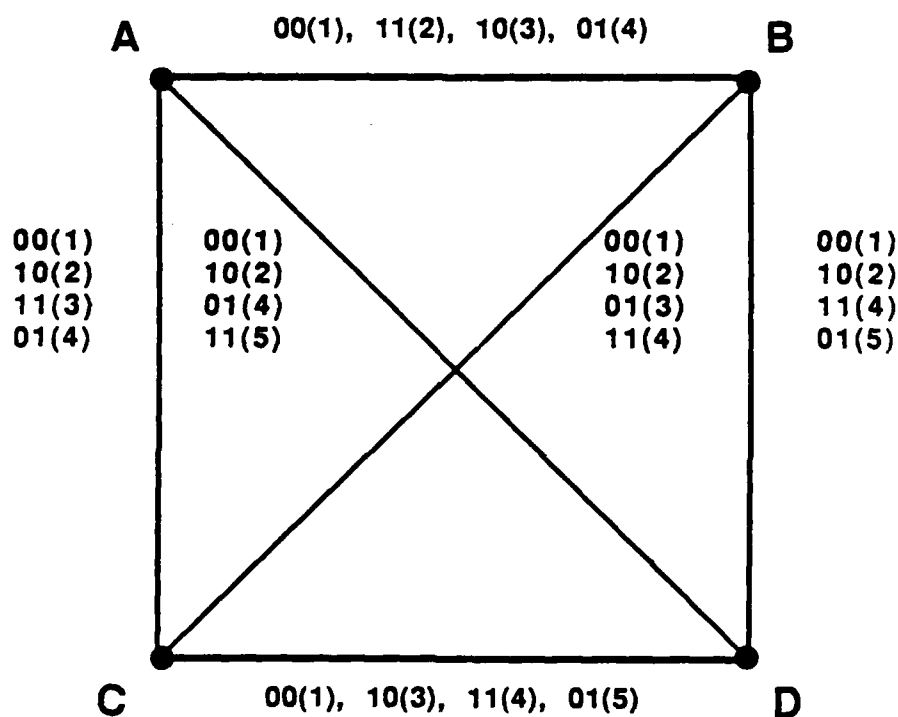


FIGURE 8 GRAPH DEMONSTRATING THAT THE SCANNING SEQUENCE OF LENGTH 5 OF TABLE 2 CAN SATISFY ALL ANTENNA CONFIGURATION FOR ALL PAIRWISE COMBINATIONS.



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from an arbitrary direction, may offer poor communication efficiency. That is, the communication capacity may be reduced by the time "wasted" looking in directions in which there are no nodes.

One can increase the number of network nodes by increasing the frame duration in integer multiples of M^2 dwell times. For a frame duration of LM^2 the maximum number of network nodes N is given by

$$N = (M-1)^L \quad (1a)$$

$$N = M^L \quad (1b)$$

The larger number of Equation 1b corresponds to the case where the $M-1$ Latin squares are augmented by the cyclic enumeration square.* The frame duration to support the N nodes is only

$$T_f = M^2 \cdot \log_{M-1} N \quad (2a)$$

$$T_f = M^2 \log_M N \quad (2b)$$

Clearly by increasing L it is possible to achieve an arbitrary large maximum number of network nodes. The number grows exponentially with L while the frame duration grows only linearly. An N node network requires a frame duration of $N-1$ dwell times to support full mesh connectivity. Thus, for a large enough network it may not be possible to support full connectivity in the beam acquisition frame duration. In such a case one could increase the frame duration to support the communication load. The important point is that the beam acquisition frame duration not greatly exceed the duration required for the communication load. If this were the case inefficient communication would result - if the same frame structure were used for both beam acquisition and for communications.

The above discussion is by nature general since there are many possible configurations in the real world. For example, it is very likely that there will be multiple terminals or

* That is, M identical rows of the M integers in natural order.

nodes within a common beam. Fortunately, it is unlikely that the different nodes would have their beams pointed in the same direction simultaneously. Spread spectrum modulation used on the beam acquisition signals may permit simultaneous access. However, for the communication signals it is probably best to time share the beam.

Also, many nodes may not be within line of sight of each other and therefore cannot communicate directly with each other. Both of these situations make it difficult to assess the communications efficiency in an operational environment.

6.4 ALTERNATIVE APPROACHES TO INCREASING COMMUNICATION EFFICIENCY

Perhaps the conceptually simplest approach is to use a separate frequency band and separate SPMT switch (see Figure 5) for the communication function. Information derived from the beam acquisition scanning would be used to provide beam direction information for the communication SPMT switch.

Alternatively one could time division multiplex between the two scanning patterns. Depending on the net entry time requirements different frame sizes could be provided. For example, the most rapid net entry would be achieved by alternating between the acquisition and communication scanning patterns. Greater communication efficiency could be achieved by inserting the acquisition scanning pattern less frequently, e.g., nine communication scanning patterns followed by an acquisition scanning pattern.

6.5 PRACTICAL NETWORK EFFECTS AND THEIR EFFECT ON BEAM SCHEDULING

The previous sections discussed beam scheduling under several idealized assumptions. First, we assumed that $N(N-1)/2$ beam patterns could be formed such that each beam pattern connects two and only two nodes thereby preventing interference from or collisions with unwanted transmissions. Such an idealized beam pattern will not occur at all times and each beam of a link between two nodes may include one or more other nodes. Thus, interference or collisions could result.

This problem can be resolved in two ways. The first method deals with collision by the slotted ALOHA method used in the packet radio network [Ref. 5-1]. That is, the packet is saved until receipt is acknowledged from the other node. If no ACK is received, the packet would be retransmitted in a subsequent frame according to a probabilistic decision. The acceptability and performance of the protocol has been established for tactical networking. The use of steerable beams only reduces the probability of collision and increases the probability of successful message transmission on the first trial. Thus, the slotted ALOHA collision protocol can be quite effective in dealing with multiple beam occupancy.

A second approach is to increase the frame duration by adding time slots in each beam with multiple nodes. The additional slots will permit sequential transmission by each node thereby avoiding collisions. Superior performance is achieved by the second method since collisions are avoided. Unfortunately, in this case, the design of the beam time plan is more much complex and a control system must be developed to coordinate the network nodes.

A second idealized assumption is that full connectivity is assumed. In practice, not all terminals will be in direct communication with each other, i.e., some terminals will be "hidden" from each other. This presents two problems. First, a beam scheduling based on full connectivity will result in unused beam slots. As a result it might be possible to shorten the frame size. However, in a mobile situation the network connectivity will change as a function of time and it is desirable to design a fixed beam frame structure that can support a fully connected network. The alternative of continually adapting the beam frame structure to match a changing node connectivity matrix is operationally very undesirable.

The second problem is that a hidden terminal may have difficulty determining the beam frame structure from observations of transmission from a few nodes. In fact, a node may be hidden from all transmissions and must perform the net entry function before communicating with other nodes.

It should be noted that the propagation circumstances that result in two terminals being hidden with respect to each other are not always bad. "Hidden" terminals cannot interfere with each other.

Third, our prior considerations neglected the effect of switching delays on the beam scheduling algorithms.

The switching times are function of the power level involved and the frequency band. For average power levels below 1 or 2 watts an electronic switch is possible. Switching speeds as fast as 10 nanoseconds are possible but typical switching speeds are a few microseconds. The corresponding beam dwell time is approximately 20 microseconds. For average powers in excess of a few watts, it is necessary to use electromechanical switches. The crossover power level between electronic and electromechanical switches is to some extent a function of frequency. For the lower frequencies electronic switches can handle more than a few watts. A typical switching speed for electromechanical switches is 20 ms. The associated beam dwell time should be at least 200 ms.

Thus, for higher power level systems the timing accuracy requirement is on the order of 10 ms. For lower power systems the timing accuracy requirement is in the range of a few tens of nanoseconds to several microseconds.

Fourth, and finally, the beam scheduling algorithms are effected by the network geography. The achievable time precision is also a function of the factors previously described but also of the geographical placement of the network nodes. The propagation time between the various nodes is of great importance. Network distributed over relatively small areas, perhaps 10 miles for tactical LOS systems, have maximum propagation delays between nodes of 50 microseconds. In this case, assuming fast acting switches the beam dwell time should be at least 500 microseconds.

However, if one assumes airplanes are potential network nodes then the distance between nodes may reach 300 miles, a value often assumed for JTIDS applications. In this case the propagation delay between network nodes may be as high as 1.5 ms. Beam dwell times for such an application should be at least 15 ms.

The significance of the communications delay and efficiency problems can be best assessed by considering some examples reflecting both switch and propagation delays. We begin by considering the range of dwell times required for the four representative operational environments presented in Table 6-6. For the low power case we assume a switching time of 2 microseconds (electronic) and for the high power case 20 ms (electromechanical). For the short range situation we consider the maximum range between

line-of-sight nodes to be 10 miles. For the long range case we consider the maximum line-of-sight range to be 300 miles. The dwell times associated with the four possible combinations are presented in Table 6-6 under the assumption that the dwell time should be ten times the larger of the switching time or the propagation delay.

The beam acquisition scanning frame time and/or communicate frame time is a multiple of the dwell time. The multiplying factor is a function of the number of network nodes and the number of beams. Table 6-7 presents the number of dwell times per beam scanning acquisition frame as a function of the number of beam elements (M) and the number of network nodes (N). Whenever the entry for dwell times per frame is greater than or on the order of the number of network nodes the communication efficiency is high and it should not be necessary to use a separate communication frame.

From Table 6-7 one can see that high communication efficiency is obtained for 4 nodes with 4 beams, for 512 nodes with 8 beams, for 4096 nodes with 16 beams, and for 32,768 nodes with 32 beams. Clearly, an 8 or 16 beam system is capable of providing an adequate communication efficiency and number of network nodes - provided that the communication delay is not excessive.

Tables 6-8, 6-9, and 6-10 present the frame durations for the cases of dwell times of 0.5 ms, 15 ms, and 200 ms, respectively. From Table 6-8 we see that if the beam scanning frame time is to be less than 0.5 ms the number of nodes must be fewer than 4,096. Related conclusions can be drawn from Tables 6-9 and 6-10. It may also be seen that for a given number of network nodes (N) the smaller M the shorter the beam scanning frame duration. While small M is also desirable from a complexity viewpoint, smaller values of M lead to greater network interference and poorer LPI and AJ performance.

For the longer range low power situation (Table 6-9) one may reasonably expect the scanning frame duration to reach 3 seconds for a modest number of beams and a reasonable number of network nodes. Use of electromechanical switches (as required for high power levels) leads to such excessively long beam scanning frames that one cannot reasonably expect to time division multiply the beam acquisition scanning frame with the communication frame. In this case it would be preferable to use a separate frequency band and a separate beam switch for the communication function. Since this leads to considerable equipment complexity it is preferable to use lower power levels.

TABLE 6-6

BEAM DWELL TIMES FOR FOUR REPRESENTATIVE SITUATIONS

<u>RANGE</u>	<u>POWER LEVEL</u>	
	<u>LOW</u>	<u>HIGH</u>
SHORT	.5 ms	200 ms
LONG	15 ms	200 ms

TABLE 6-7 BEAM ACQUISITION FRAME TIME

M \ N	4	8	16	32	64	128	256	512	1024	2048	4096	8192	16384	32,768
	4	16	32	48										
8					128		192							
16			256			512					768			
32				1024										2048

Table 6-7 - Beam Acquisition Frame Time (measured in dwell times) as a function of the number of beams (M) and network nodes (N). It is assumed that any nodes in excess of M are accommodated by the frame replication technique described earlier. In many cases more compact realizations are possible.

TABLE 6-8 BEAM ACQUISITION FRAME TIME

M \ N	4	8	16	32	64	256	512	4096	32,768
4	8		16		24				
8		32			64		96		
16			128			256		384	
32				512					1024

Table 6-8 Beam Acquisition Frame Time (in ms) as a function of the number of beams (M) and number of network nodes (N) for the case of a beam dwell time of 0.5 ms.

TABLE 6-9 BEAM ACQUISITION FRAME TIME

M \ N	4	8	16	32	64	256	512	4096	32,768
4	0.24		0.48		0.72				
8		0.96			1.92		2.88		
16			3.84			7.28		41.32	
32				15.36					30.72

Table 6-9 Beam Acquisition Frame Time (in seconds) as a function of the number of beams (M) and the number of network modes (N) for the case of a beam dwell time of 15 ms.

TABLE 6-10 BEAM ACQUISITION FRAME TIME

M \ N	4	8	16	32	64	256	512	4096	32,768
4	3.2		6.4		9.6				
8		12.8			25.6		37.4		
16			51.2			102.4		153.6	
32				204.8					409.6

Table 6-10 Beam Acquisition Frame Time (in seconds) as a function of the Number of Beams (M) and the Number of Network Nodes (N) for the case of a beam dwell time of 200 ms.

SECTION 7

USE OF ADAPTIVE BEAM ANTENNAS SYSTEMS WITH EXISTING COMMUNICATIONS MODEMS

The adaptive beam antenna system proposed in this report can be used with any existing AF communication modem. This would be accomplished by operating the beam acquisition signal in an adjacent passband. The information derived on the location of the other node(s) would be passed to the communication system, which consists of modems, antenna ports, and a switch for use in establishing the desired link(s).

A much more interesting situation exists in the network environment when one attempts to determine the impact of the adaptive beam antenna system on a truly networked radio system capable of operating in a burst format through the switched beam antenna system. The following two sections determine the impact of the adaptive beam antenna system on two versions of a packet radio network - one using the ALOHA protocol and the other the CSMA protocol.

7.1 PERFORMANCE OF AN ADAPTIVE BEAM PACKET RADIO NETWORK USING ALOHA RANDOM ACCESS

The advantages of using adaptive beam antennas can be assessed by comparing two Aloha random access PR nets - one with omnidirectional antennas and the other with adaptive MBAs. The comparison is the ratio of the average channel traffic to the average data message rate or G/S . The portion of this factor greater than S corresponds to the retransmitted packets caused by collisions. These retransmissions significantly increase the average message delay.

Our performance comparison is based on the following assumptions. All N nodes are assumed to have identical and uniform traffic statistics. It is assumed that at each node the probability of distribution of the other nodes is uniform over the M beams. Unslotted Aloha random access is assumed.

It may be shown [Ref. 7-1] that the channel traffic (measured in packets per packet duration) G is related to the supported message traffic S by

$$S = Ge^{-2G} \quad (1)$$

where S and G represent the total network traffic for the omnidirectional antenna case. The same formula applies for the MBA case except that we use new variables where the super prime indicates the MBA case

$$S' = G'e^{-2G'} \quad (1')$$

with the MBA system the average message traffic observed in each receive beam is given by

$$S' = S[1/N + (N-1)/N \cdot M] \quad (2)$$

where the first term in the brackets is the message traffic transmitted at that node and the second term corresponds to the average traffic observed in that receive beam from the rest of the network.

As an example of the performance gain achievable consider the case of a 10 node network with each node having 8 beams. Suppose for the omnidirectional case that the message traffic were quite high, e.g., $S = 0.15$, so that a considerable number of collisions occurred. For this case the channel traffic is $G = 0.243$ corresponding to a 62% increase owing to collisions.

For the MBA case the average message traffic per receive beam is $S = 0.031875$ and the channel traffic G is only 7% higher. Thus, a very significant improvement is achieved in communication performance (not to mention the AJ and LPI advantages.)

The advantages are substantially greater than indicated above since the additional link budget gain of $20\log_{10}M$ could be used to speed the burst rates by a factor of 64 thereby proportionally shortening the packets and reducing collisions or offering more bits per packet. In other words with the MBA system one could offer a total network bit rate 64 times larger than for the omnibeam case while offering better packet delivery times owing to the reduced number of retransmissions.

With existing and planned packet radio equipment it is not possible to increase the burst rate by a factor of 64. However, it is possible to increase the burst rate by a factor of 4 to 400 kbits/s when multipath conditions so permit. Use of directional beams reduces multipath and as a result we can expect the MBA system to offer a four-fold improvement in average network data rate.

7.2 CARRIER SENSE MULTIPLE ACCESS (CSMA)

CSMA is commonly employed in packet radio networks to improve performance by avoiding collisions when it is clear that the channel is occupied. The principal performance limitation with CSMA in conventional omnidirectional beams is created by "hidden" terminals. For example, two networks may be able to communicate directly with a third node yet not be able to communicate directly with each other. In this case the first two nodes are hidden with respect to each other. CSMA will not be effective in avoiding collisions at the third node.

Use of MBA antennas will tend to significantly increase the number of hidden terminals and make CSMA a less effective protocol. One alternate approach would use an omnidirectional CSMA receive beam of each node. Unfortunately, this protocol might fail to detect pulses pointed at the third node and also might respond to pulses aimed at some other node. Thus, the use of an omnidirectional CSMA beam does not appear to be desirable.

The most efficient multiple access scheme simply modifies the acquisition scanning algorithm to produce a time-switched scheduled communication beam steering algorithm such that collisions are impossible.

In summary the CSMA protocol is not effective for an adaptive multibeam antenna network. On the other hand the directionality of the adaptive beams greatly reduces the need for collision avoiding protocols.

SECTION 8

DEMONSTRATION SYSTEM PLAN

8.1 RECOMMENDATIONS AND CONCLUSIONS OF THE STUDY

We conclude that an adaptive beam antenna system can offer very substantial performance improvements in a network environment. The AJ and LPI performances are enhanced by the antenna directivity. Furthermore the link power budget is greatly improved while the narrow beamwidths reduce the multipath interference as well as the interference or self-noise from other network nodes. The magnitude of these improvements depends on the antenna system parameters but under reasonable assumptions the enhancements are substantial, e.g., 6 dB or more.

Furthermore, we conclude that these improvements may be obtained with practical cost-effective hardware.

We recommend that beam scanning be accomplished using the narrowest achievable beamwidth from a single MBA element. This approach is not only simplest but was shown to offer the best performance in a network environment. The beam acquisition algorithm based on Latin square scanning guarantees connections (when physically possible) with all network nodes in a near minimal time. The beam scanning pattern can be readily extended to accommodate an arbitrary number of network nodes. Unsynchronized net entry can be performed using a modified selective scanning algorithm that is compatible with the Latin square scanning sequences.

Furthermore, since the same scanning pattern is used for transmit and receive the algorithm minimizes the hardware complexity. As a result, we recommend the Latin square scanning beam acquisition algorithm developed in Section 5.

The resulting system is capable of working with any existing communication modem signals in a separate frequency band and controlling the beam selected for communication on the basis of information derived from the beam acquisition signal modem.

Alternatively, if one so desired it is possible to develop an integrated system in which the beam acquisition and the communication modems shared the same time-variant beam pattern. Of course, in this case the communication modem would have to be capable of operating in a burst format such as used in the Packet Radio Network.

8.2 ANTENNA SYSTEM DEVELOPMENT RECOMMENDATIONS

Based on our investigation the proposed adaptive beam antenna systems are completely within the state-of-the-art. No new technological breakthroughs are required to make our system concepts practical. Thus, we do not propose any development of enhanced technology components.

However, while not necessary under most circumstances, new technology would prove beneficial to the proposed antenna systems. Specifically, technological developments that produce lower cost components such as switches, diplexers, and LNAs will make adaptive beam antenna systems more practical. With lower cost components some of the system configurations judged impractical in Section 2 would prove to be useful.

In addition, development of low-cost fast-acting switches capable of handling high power levels could be very useful in certain circumstances. If high power levels, 10 watts or more, are required, development of fast-acting electronic switches could reduce the beam acquisition frame time by a factor as large as 1000 or more.

Needless to say, an improvement on this order could make an impractical system design a practical system design. Specifically, the beam tracking sampling time and the communication delay could be reduced to acceptable levels.

Thus, our major technology development recommendation is for efforts leading to higher power (perhaps as much as 1 KW) single-pole multiple throw electronic RF switches.

8.3 DEMONSTRATION SYSTEM CHARACTERISTICS

Based on this study we recommend that the demonstration system have the following characteristics. These are preliminary estimates pending detailed reconsideration as the first task of Phase II.

The adaptive beam MBA system should provide circular coverage using eight helical antennas with circular polarization. The system should operate at approximately 1.6 GHz so that practical dimensions result with low-cost components. A three-node system is sufficient to demonstrate network operation. The beam acquisition signals should use DS spread spectrum modulation.

8.4 DEVELOPMENT PLAN

Our development plan for a demonstration system consists of five tasks. First, we will review the preliminary system characteristics and revise them in cooperation with AF technical guidance. The finalized system characteristics will be presented for AF approval at the preliminary design review meeting.

The second task will consist of detailed system design. This design will be reviewed with AF technical personnel at the critical design review meeting. On approval the third task is to implement the design. The fourth task is testing of the subsystems and finally the overall system. The fifth and final task is to demonstrate a 3-node network operating in the acquisition and the tracking modes.

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